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Uncertainties in future energy demand in UK residential heating

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HIGHLIGHTS

- Quantified scenarios show high uncertainty for UK residential space heating to 2050.
- There is a high risk of gas lock in without policy intervention.
- Some electrification of heating is very likely to be needed to meet climate policy goals.
- High electrification raises challenges including peak winter electricity demand.
- More diverse strategies including energy efficiency and biofuels have lower risks.

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ABSTRACT

Fossil fuels are the main source of space heating in the UK, and therefore climate mitigation implies a systemic change in space heating systems. The challenge is difficult because of an inefficient building stock and high penetration of natural gas. We present new quantified scenarios for residential energy use in the UK to 2050. With minimal policy intervention the UK will remain locked into a gas based heating system, which would conflict with the policy goal of decarbonisation. However, there is a range of scenarios in which this is avoided. A system heavily reliant on heat pumps powered by low carbon electricity is UK policy makers' currently preferred alternative. We conclude that some shift in this direction is likely to be required, but complete reliance on this solution raises a number of problems. Greater use of energy efficiency and biomass can also play a significant role. These options have different risks, but a more diversified strategy would be more prudent. We conclude that the future of UK residential space heating is very uncertain, but meeting low carbon heating goals is better conceptualised as reducing reliance on gas rather than necessarily mass electrification. Our analysis has implications for any country with high use of fossil fuels in space heating and ambitious decarbonisation goals.

1. Introduction

In terms of the energy challenges provided by residential heating the UK is, in many ways, a paradigm case for the developed world. The challenge is that there is an inefficient building stock, with relatively slow and piecemeal refurbishment; the climate is cool and temperate, so that heating is a much more significant energy service than cooling; and the energy supply infrastructure is well-established with a very high penetration of natural gas, which has historically been cheap. The result is that the residential sector is an important user of energy and main end use sector for natural gas, the majority for space and water heating in gas boilers. Long term trends have seen rising household numbers and internal temperatures drive increased heating service demand. Although homes built in the last four decades have been subject to energy performance requirements, their energy use for heating is only slightly lower than older dwellings (Hamilton et al., 2013). Until the last decade, these trends outstripped increases in energy efficiency in building fabric and heating systems, so that energy demand rose. From 2004 to 2012, this trend reversed. In the absence of lower internal temperatures (for which there is no evidence), this is due some combination higher prices and public policy driving improved energy efficiency (Summerfield et al., 2009). Large programmes to install loft and cavity wall insulation and condensing boilers have outpaced rising service demands, so that residential heating energy fell over this period. However, the rapid decline in energy efficiency activity since 2012, due to policy changes during a period of high energy prices, clearly indicates that public policy rather than prices tends to be the key driver (Rosenow and Eyre, 2013). This more recent evidence

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suggests that the period 2004–2012 may be an atypical period characterised by the availability of relatively easy, low cost energy efficiency improvements and an effective policy framework to deliver them and that this trend is now likely to change due to the declining availability of low cost measures and the recent large reductions in the scale of UK residential energy efficiency programmes.

At the same time, the UK has adopted a legally binding commitment to reducing greenhouse gas emissions by 80% by 2050, with the need for significant progress by 2030. There is broad agreement that this is incompatible with retaining a residential heating sector with anything like the current structure.

There is, therefore, an apparent disconnect between ambitious goals and historical trends. On the one hand, the rates of change required to meet climate goals are large; on the other the rates of change of heating systems and practices have typically been rather low. This paper seeks to explore the uncertainties implicit in this disconnect by examining the uncertainties in future residential heating demand in the UK.

Section 2 explores the different narratives that have been developed for UK residential heating futures in the context of the low carbon transition. Section 3 sets out the different qualitative socio-technical scenarios examined. Section 4 describes the methodology employed for quantification of different key uncertainties and Section 5 gives the results. We end with a discussion of the implications for policy in Section 6 and conclusions in Section 7.

2. Low carbon heating transitions

Early explorations, e.g. (PIU, 2002; RCEP, 2000) of the UK residential sector heating implications of deep carbon mitigation focussed on the continuation and reinforcement of trends, with greater use of efficiency, CHP and on-site renewable energy. These were in the context of calls for a 60% reduction in emissions by 2050 and, even with this target, a greater use of zero carbon vectors was found to be needed in higher growth scenarios (PIU, 2002). With the change in the UK's 2050 target to an 80% reduction, in the 2008 Climate Change Act, a new narrative emerged (CCC, 2008; Ekins et al., 2010; HMG, 2009) of large scale conversion to low carbon electricity (with this assumed to be the norm for UK supply after 2030). These latter results emerged from economy wide assessments, using optimisation models, with rather limited detail on the diversity of the building stock and the practical issues involved in its refurbishment. They also use only a single projection for demographic and economic growth. However, there is also evidence of the potential value of electrification in decarbonisation of heating from more detailed analyses of the building stock (Lowe, 2007). The potential for mass electrification of heating has been received with some scepticism in the building energy research community, with a number of critiques of the feasibility of near-universal deployment of heat pumps (Eyre, 2011; Fawcett, 2011; Hoggett et al., 2011; Speirs et al., 2010).

Following these critiques, there has been some moderation of the role of electrification of heating in the most recent UK policy statement (DECC, 2013b). In the light of rather slow progress in heat pump deployment, the strategy now includes a greater role for heat networks in dense urban areas. Concerns about the medium term implications for increasing electricity demand have been addressed by allowing for large scale use of some intermediate technologies in the 2020s and 2030s, notably gas-fired absorption heat pumps and hybrid boiler/heat pump systems. However, as neither technology has yet been deployed at scale, assumptions about rapid and widespread deployment (i.e., for most households at the next point of heating system change) raise some interesting issues.

The UK has much lower levels of deployment of heat networks than most other northern European countries. Bulk movement of heat has no intrinsic merit and requires significant capital investment. However, whilst most district heating, in most countries, has been gas-fired, heat networks can utilise a diverse range of heat generating technologies, including waste to energy schemes, waste heat from power generation and industry, biomass and large heat pumps. They therefore enable a range of low carbon heating strategies.

The use of dedicated biomass, in principle, can supply large amounts of energy for heating, through a variety of vectors – wood in building-scale boilers and stoves, larger boilers (without or without combined heat and power) to supply heat networks, bioliquids to replace oil fuels and biogas. The global resource is potentially very large but raises problematic issues with respect to land use; the potential UK resource is substantial (Slade et al., 2011), but unlikely to supply a large fraction of UK heat. With constrained supply, choices will need to be made between using biomass in heating, transport and power generation (Jablonski et al., 2010).

Whilst the current demand for energy for residential heating is well known and unlikely to change quickly, very significant changes are possible in the long term through changes to energy services demand and/or energy efficiency. It is well established that the thermal efficiency of both new and refurbished buildings can be better than current typical practice by a large factor (Urge-Vorsatz et al., 2012). However, real world practice to date has been less encouraging with a major gap between planned and actual energy performance (Chiu et al., 2014; Hamilton et al., 2013).

In these circumstances, predicting the future of UK residential heating energy is fraught with uncertainty. It depends on the nature and extent of the commitment to delivering 2050 climate targets, as well as a range of technological, social and institutional factors that affect building energy efficiency and heating system choice. Key uncertainties include future heat demand, driven by comfort needs and insulation levels, and the penetration rates of different low carbon heating fuels (biofuels, solar and electricity). Trends in both areas depend on decisions about refurbishment that are strongly affected by technical change, prices, social norms, building industry skills and supply chain capacity. Lower heating demand and fuel switching potentially interact anti-synergistically, as high capital cost heating systems inevitably will be less economically attractive for buildings with low heat demands.

Other uncertainties include the scale of the most basic drivers of housing demand – population growth and household size – which have been neglected in previous studies in this field.

3. Scenario descriptions

Our approach has been to consider the future of residential sector heating in the context of the different infrastructure strategies that the UK might adopt over coming decades. As the world's first industrialised country, the UK has some very old urban infrastructure and therefore faces some challenges earlier than other countries (Hall et al., 2014; Tran et al., 2014). Potential strategies that might be adopted for energy infrastructure as a whole, and our broad approach to quantifying them, are set out elsewhere (Baruah et al., 2014a). The strategies that might be adopted all seek to deliver a high level of energy security, as we normatively assume that this policy goal is extremely unlikely to be abandoned in any highly developed modern economy. We treat other current policy objectives, notably affordability and carbon emissions reduction, differently, recognising that priorities within these might change and that the effectiveness of different technologies to meet these goals and other social aspirations is inevitably uncertain on long timescales. Divergent futures are possible as any specific technical solutions adopted can lead to path dependence and lock-out alternative options (Unruh, 2000). We therefore use a scenario approach to understanding the range of possible future socio-technical systems in which different technical, social and policy changes lead to different pathways.

We focus on four broad scenarios, described in Sections 3.1–3.4 below, that emerge for residential space heating. We recognise that this, like all scenario exercises, is arguably over simplistic. The intention is that they map the space within which actual futures are likely to fall. Even so, they neglect some possible futures, including large scale deployment of energy storage technologies and/or use of hydrogen.

3.1. Minimum policy intervention (MPI)

In this scenario, there is no significant strengthening of UK energy policies to meet climate mitigation goals, and therefore longer term carbon targets requiring very significant decarbonisation are not a driver of residential heating policy. Concerns about energy security continue and ensure that there is sufficient investment in electricity and gas infrastructure and supply to ensure reasonable levels of energy security in heating and other energy services. The recent decline in energy use in the sector comes to an end, as efficiency programmes stall; longer term growth trends in energy demand are reasserted with upward pressures from population and economic growth only partially offset by improvements in energy efficiency. Only limited change is driven by regulatory standards, tax incentives and support programmes. The energy supply sector changes rather slowly, with continued dominance of large scale, fossil fuel investments by large companies. There is no significant investment in nuclear or carbon capture and storage (CCS). Renewables investment continues as costs fall, but capacity increases only slowly. Smart meters begin to be rolled out as currently planned in 2015, but there is no need for significant use of demand response to balance the electricity system. Power sector investment continues to rely largely on combined cycle gas turbines (CCGTs) with gas supplies from largely imported, but diverse, sources. In these circumstances, residential heating remains largely dependent on gas with modest continued efficiency improvements in building efficiency. Innovation is not a priority in the sector, and the heating services industry structure remains broadly unchanged.

3.2. Electrification of heat and transport (EHT)

In this scenario, there is a continued emphasis in the UK on strong climate policies with future targets generally met. Energy and climate policy remain centralised. Concerns about energy security continue and are addressed by large investments in low carbon electricity generation. Existing long term trends in demand continue due to upward pressures from population and economic growth. The impacts of these on demand are offset to some extent by improvements in building energy efficiency, but the priority on the demand side is increased electrification of demand of heat (and transport). Smart meters are rolled out and increasingly used in demand response programmes in all demand sectors. Distributed solar PV adoption is moderate. Control of electric vehicles and building heating systems becomes critical for the effective management of electricity loads. There are rapid increases in the capacity of electricity generation, especially after 2030. Transmission and distribution networks are strengthened and additional transmission lines built where needed. The gas grid falls into decline and large parts are decommissioned by 2050, with most heating of buildings electrified. The large and rapid investment in low carbon power generation technology is delivered by the incumbent large companies. Within this broad scenario, it is possible to set out a number of possible electricity supply options, depending on the balance between offshore wind, fossil fuels with carbon capture and storage, and nuclear. These are explored elsewhere (Baruah et al., 2014a), but the low carbon supply side choices have limited impact on heating scenarios.

3.3. Local energy and biomass (LEB)

In this scenario concerns about energy security continue, but faith in national government and its institutions to deliver this outcome is eroded. Concerns to protect energy security are reflected in much greater emphasis on individual and small scale action, with more reliance on local resources, in particular solar energy and locally produced biofuels. Existing long term trends in demand are reduced as upward pressures from population and economic growth are more than offset by higher efficiency heating systems (heat pumps and CHP) and moderate improvements in building fabric energy efficiency, stimulated by a combination of Government policies and rising awareness of energy security driving local action. After 2020, solar PV costs fall to below the costs of retail electricity and solar energy deployment becomes mainstream for companies and households, reducing net building electricity demand, although leaving peak (winter evening) demand unaffected. Smart meters are rolled out, initially with a high emphasis on consumer information and demand reduction, although their capability to support diurnal demand response is then valuable. New demands for electricity in heating are more moderate than in the EHT scenario. The electricity supply sector changes steadily. Initial investment is largely in wind, with greater acceptance of onshore wind turbines, and much increased diversity of ownership, including by community groups, local authorities and cooperatives. There is increased deployment of distributed generation, resulting in a more active role for electricity distributors. The emphasis on local fuels leads to more use of bioenergy from local sources for heating. A number of bioenergy business models emerge, including solid fuel use in household scale wood pellet boilers and wood chip stoves, some larger biomass CHP systems, biofuels to replace oil-fired systems and biogas from a variety of sources, used both directly at the point of production and through introduction into the existing gas grid. The key similarity of all the approaches is that heating is decarbonised more through modifications of the existing infrastructures for solid, liquid and gaseous fuels, rather than via electrification.

3.4. Deep Decarbonisation with Balanced Transition (DDBT)

In this scenario, there is a continued emphasis on strong climate policies with existing targets met. Social acceptance of the need for energy system transformation leads to strengthened and consistent government policy, as well as greater decentralised action. Concerns about energy security continue and are addressed in part by large investments in energy efficiency, with a mix of low carbon energy sources, including microgeneration driven by significant carbon prices. Low carbon electricity generation and biomass technologies are adopted, but less strongly than in the EHT and LEB scenarios respectively; and the economy becomes more electrified with less dependence on natural gas. There continues to be a high level of energy security. Previous long term trends in demand growth are never reasserted. Upward pressures from population and economic growth continue to be more than offset by improvements in energy efficiency, stimulated by a combination of active policy and rising awareness. Smart meters are rolled out and used effectively for both demand response and demand reduction. In buildings, significant efficiency improvements in both fabric and heating systems, coupled with greater conservation, drive a major reduction in heating final energy demand. The performance gap between design efficiency and actual energy use is addressed, with greater user engagement in energy issues and improved supply chain skills, although the level of efficiency achieved still does not reach that of the most optimistic predictions. Residual demand is met by a combination of low carbon technologies, including heat pumps and micro-CHP in homes and through heat networks in large urban areas. This is the only scenario in which district heating plays a significant role, with local authority led initiatives in cities, largely supplying urban centres. Most schemes are based on large commercial and/or public sector heat loads, but also supply neighbouring residential areas, where the heat density is sufficient to justify this. The potential heat sources are diverse and location dependent. We assume most comes from waste to energy schemes and waste heat from power generation, with some residual gas-firing. However, it is clear that other options are possible, including bioenergy crops and large heat pumps, which are more efficient than single building scale heat pumps (Blarke and Lund, 2007). Given the penetration assumed for heat networks is assumed to be limited to dense urban areas, our overall results are not very sensitive to these choices. Solar PV and solar thermal costs fall and they are adopted widely. The electricity supply sector changes quickly with rapid investment in low carbon power generation technologies, so that the UK decarbonises electricity supply very quickly up to 2030. Renewable technologies capture a high market share in the electricity supply mix, with gas-fired generation used at low load factors to provide continued flexibility in the face of high levels of intermittency.

4. Methodology

Our basic assumption is that there are two categories of uncertainty that are broadly separable.

The first category is uncertainty in broad socio-economic trends that are normally considered exogenous to the energy sector, primarily population and economic activity. Engineering-economic models of space heating demand implicitly assume that socio-economic uncertainties are manifested through impacts on the floor area and the temperature to which it is heated. The key underlying drivers of these are likely to be population and income. The former drives housing demand (and therefore housing construction and supply); the latter potentially affects floor area, internal temperature and refurbishment rate. Our methodology assumes that the service demand for heating is principally driven by population, but the quantitative outputs are probably better understood as resulting from the combined uncertainty of socio-economic drivers of service demand. As our principal aim is to assess the potential scale of overall socio-economic uncertainties, it is important to avoid double counting. Income effects on internal temperature in the UK are only ~0.6 C between the highest and lowest income groups (Kelly et al., 2013), so neglecting income effects is an acceptable simplification, unless either income inequality or the energy price/income ratio increases significantly. By allowing for socio-economic uncertainties our approach contrasts with the overwhelming majority of long term energy and carbon emissions scenarios for the UK, including the major policy assessments, e.g. (CCC, 2008; HMG, 2009), which neglect these uncertainties completely, by using the mid-range number from the relevant official UK Government projections (e.g. Office of National Statistics population projections and HM Treasury projections of economic growth). Given the implications of population for infrastructure this is a surprising omission from most long term energy analyses. Neglect elsewhere is a major reason for our decision to assess its effects.

The second category of uncertainty is socio-technical-the future trajectory of UK energy system futures. To understand these implications we use the scenarios set out above. For each qualitative scenario, we use expert judgement to specify the quantitative trends in socio-technical variables in the period 2010–2050, from which we compute residential heating energy demand. These include conservation measures and heating controls (via internal temperature change), improvements in building fabric thermal performance, heating system efficiency, use of onsite heat and power production and other heating system technology change (including fuel switching).

Fig. 1 shows a taxonomy of the drivers of residential heating energy demand. Drivers not directly modelled in this study are light coloured. The logic of these choices is as follows: dwelling type is only significant in so far as it affects thermal performance, which we model directly; average floor area is captured in the

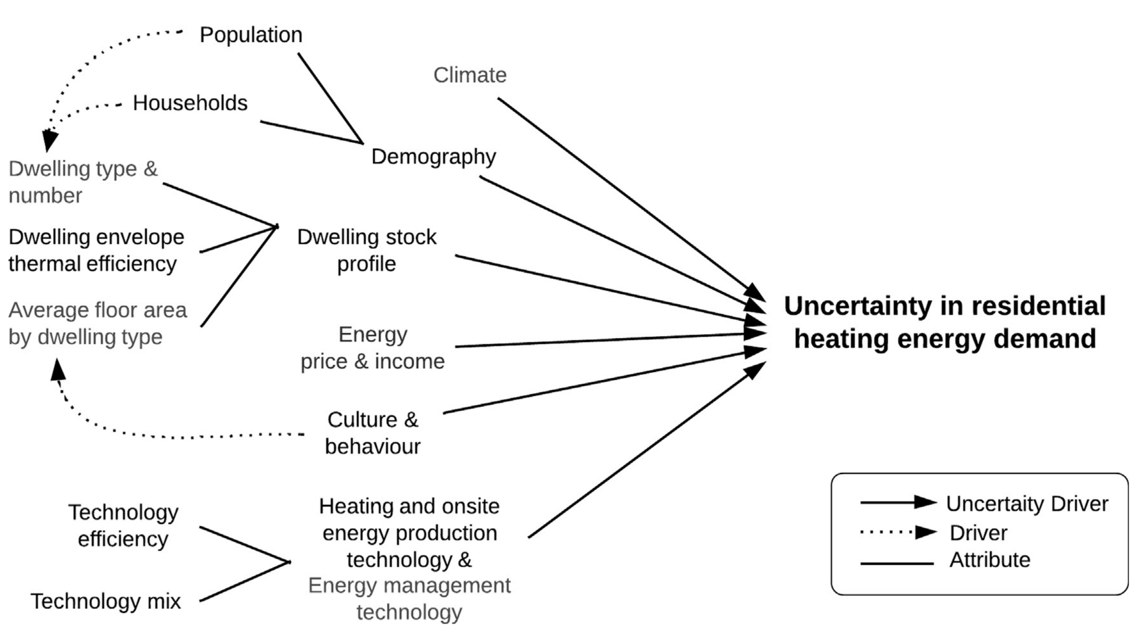

Fig. 1. Residential heating demand drivers.

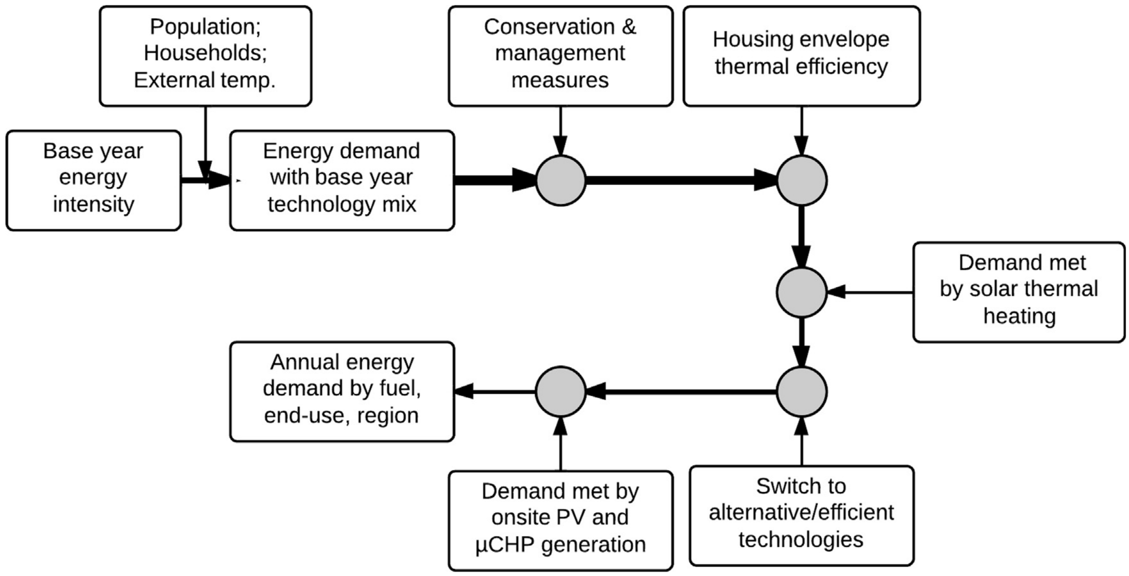

Fig. 2. Modelling process to calculate residential energy demand.

stock profile as part of our metric of envelope thermal efficiency; energy management technology improvements are captured in our assessment of internal temperature and appliance efficiency; energy prices and household incomes are clearly important in econometric models of energy demand but would 'double count' the changes we model through changes in energy service demands. Climate is a potentially significant influence, as changes in the differences between internal and external temperatures affect energy demand by approximately 10% per degree K (Summerfield et al., 2009). Temperature changes are dependent on scenarios of mitigation, but globally rather for the UK, any therefore mitigation scenario impacts on UK winter temperature depend on assumptions outside the scope of our analysis.

For both types of uncertainty, quantification of energy outcomes requires additional detailed assumptions to translate broad descriptions of uncertainty in model parameters. The process logic of the calculation is set out in Fig. 2, and key parameters used for each scenario are in Table 1. In essence we use a simulation-accounting model approach, with change in space heating demand over the base year (2010) modelled as a function of demand drivers (exogenous to the model) and the energy system transition parameterised as set out in Table 1. We focus on energy use for space heating, which is ~80% of residential heating demand (DECC, 2013a), although this figures varies significantly from household to household. Space heating demand with the 2010 technology mix is estimated for each of 11 geographical regions of Great Britain. (Due to data limitations we exclude Northern Ireland, which has ~2.5% of the UK population, ~3% of energy demand and a different energy infrastructure and market). Space heating demand for 2010 is weather corrected and has been validated against actual energy use. The uptake level of each socio-technical parameter is modelled each year to 2050 and space heating demand calculated by region by fuel.

In general, we use S-curves to model rates of technical change, reflecting historically observed processes of technical change (Shorrock, 2011). The seasonal performance factor (SPF) of heat pumps is an important assumption in some scenarios. We assume that the SPF of an air source heat pump (ASHP) in an individual dwelling rises from 2.00 in 2010 to 3.00 in 2050, and that of a ground source heat pump (GSHP) from 2.50 in 2010 to 4.00 in 2050. The majority of this effect derives from an assumed improvement in technology and installation practice, with a higher proportion of heat pumps operating at lower temperatures in underfloor heating as time progress. Our assessment of the impacts on peak electricity demand, in the discussion section below, recognises that efficiency at peak load will be lower as external temperatures are lower at times of peak demand. To calculate the efficiency at peak load, we apply to the seasonal performance factor an adjustment factor of 0.8, which is derived from EST heat pump trial data (EST, 2010) and consistent with other UK sources (Baster, 2011).

The model is designed to allow a wide range of heating system choices, rather than to provide a detailed state of the art assessment of any particular technical option. Our approach to the energy performance of buildings is rather straightforward. Rather than modelling heat demand through a bottom up assessment of the design thermal performance of different building types, which is notoriously bad at replicating actual energy use, we calibrate the model to actual demand in 2010 and then, for different scenarios, model the change in demand due to building fabric and occupant behaviour change, using the assumptions set out in Table 1. As the aim is to map a plausible range of futures, there is no attempt at spurious accuracy based on detailed building models.

Our approach to biomass futures is similar. We model one 'high biomass' future (the LEB scenario) based on transparent assumptions, rather than attempting to address whether this constitutes the 'best use of biomass' to meet the combination of energy policy objectives.

The full modelling methodology we have employed for quantification of energy demand and fuel mix is set out elsewhere (Baruah et al., 2014a). In this paper we focus on the approach used for residential heating and the quantitative outcomes generated.

The model has some clear limitations including:

- dwelling numbers are represented by proxies of regional population,
- no explicit price-induced effects are modelled,
- no explicit assessment of social, cultural or behavioural drivers (except as internal temperature),
- no direct modelling of technology supply chain issues (except through diffusion rates), and
- no allowance for adaptation to climate change.

Table 1
Model representation of major demand drivers and scenario assumptions.

	Model variable	Minimum Policy Intervention (MPI)		Electrification of Heat and Transport (EHT)		Local Energy and Biomass (LEB)		Deep Decarbonisation Balanced Transition (DDBT)	
		2030	2050	2030	2050	2030	2050	2030	2050
Socio-economic uncertainties									
Demography	Population (million) low; medium; high	65; 69; 80	66; 79; 97	65; 69; 80	66; 79; 97	65; 69; 80	66; 79; 97	65; 69; 80	66; 79; 97
Climate change	External temperature	no change	no change	no change	no change	no change	no change	no change	no change
Socio-technical drivers									
Thermal comfort	Internal base temperature (C)	15.5	15.5	15.5	15.5	15.5	15.5	15.26	14.5
Building fabric	Change in heat loss (%)	−1	−5	−1	−5	−7	−30	−12	−50
Heating technologies	Replacement of gas boilers with new technologies[a]	Heat pump: 0.4%, Micro-CHP: 0.3%, Biomass: 0.3%, Resistance heating: 0%	Heat pump: 3%, Micro-CHP: 3%, Biomass: 3% Resistance heating: 0%	Heat pump: 10% Micro-CHP: 0.3% Biomass: 0.3% Resistance heating: 0.6%	Heat pump: 80% Micro-CHP: 3% Biomass: 3% Resistance heating: 5%	Heat pump: 5% Micro-CHP: 2% Biomass: 3% Resistance heating: 0%	Heat pump: 40% Micro-CHP: 20% Biomass: 30% Resistance heating: 0%	Heat pump: 5% Micro-CHP: 3% District heating: 2% Biomass: 1% Resistance heating: 0%	Heat pump: 40% Micro-CHP: 30% District heating: 20% Biomass: 10% Resistance heating: 0%
Solar PV	Uptake in Watt-peak/person		30		30		240		300

[a] Fuel switching is also allowed from resistance heating, oil boilers and solid fuel boilers.

5. Results

Figs. 3–6 show the effect of different scenarios for the main fuels for residential heating in the UK.

In the Minimum Policy Intervention (MPI) scenario, recent trends driven by energy efficiency policy go into reverse, so that fuel use grows modestly over the period to 2050. Gas remains the dominant fuel, rising in use from the existing level of 230 TWh/year to over 250 TWh/year, with electricity confined to its existing market niches, largely in rural (off-gas grid) areas and flats.

In the Electrification of Heat and Transport (EHT) scenario, which most closely reflects the conventional wisdom on deep decarbonisation of heat, gas demand initially remains broadly stable, then falls quickly from 2030 to 2050, by a factor of six, to less than 40 TWh/year. As heat pump technologies and markets mature and electricity system decarbonisation allows major carbon mitigation from electrification, electricity use for space heating rises to 75 TWh/year. With an additional 17 TWh/year estimated for use in residential water heating, this doubles existing residential electricity demand.

In the Local Energy and Biomass (LEB) scenario gas demand also falls quickly from 2030, but the fall moderates by 2050 as heat pumps prove less suitable for some homes. Heat pump technologies and markets develop from 2030, but the rapid rise in electricity demand seen in the EHT scenario is not mirrored here for three reasons. First there is more rapid improvement in building efficiency; secondly, biofuels are developed as alternative low carbon fuels, using the existing infrastructure; and thirdly there is a major increase in solar PV generation in the residential sector, with a large fraction used for space heating reducing the demand on external supply. Biofuel use for residential heating rises to over 60 TWh/year, which exceeds the likely resource from wastes, but falls well within estimates for potential UK biomass production in 2050 (HMG, 2011).

In the Deep Decarbonisation Balanced Transition (DDBT) scenario, some of the same outcomes are observed as in LEB. In both scenarios gas demand continues to fall, and more quickly from 2030, but in the DDBT scenario, this is due to a combination of more radical efficiency improvement than in other scenarios and fuel switching. The fuel switching is delivered by a combination of heat pumps and larger (i.e. not micro) CHP technologies, with the latter via district heating systems in urban areas supplied with waste fuels and waste heat from power generation (supplying 27 TWh/year by 2050). In this case, the major increase in PV generation in the residential sector reduces net electricity demand to very low levels, and therefore the demand for electricity is significantly lower than in other scenarios.

Figs. 7 and 8 illustrate the impacts of population uncertainty on electricity and gas demand for low and high population projection variants for the scenarios with the highest and lowest projected demands in 2050. In each case, the only significant effect is on the dominant fuel – gas in MPI and electricity in EHT. Whilst the effects are not as radical as the socio-technical scenario effects, they are significant – typically ~25% variation, implying that population sensitivities cannot be neglected in system analysis and planning on these timescales.

It should be noted that the data presented in Fig. 7 are for residential sector gas demand. Total national demand for gas also depends on final use in other sectors and in power generation. Use in non-domestic buildings may follow some of the same trends as the residential sector, but industrial fuel substitution is widely expected to be more problematic. Like the fuel mix in electricity generation, these issues are outside the scope of this paper. However, any scenario with a very substantial share of intermittent renewable electricity, without alternative flexibility mechanisms, is likely to require back-up from flexible fossil fuel-fired

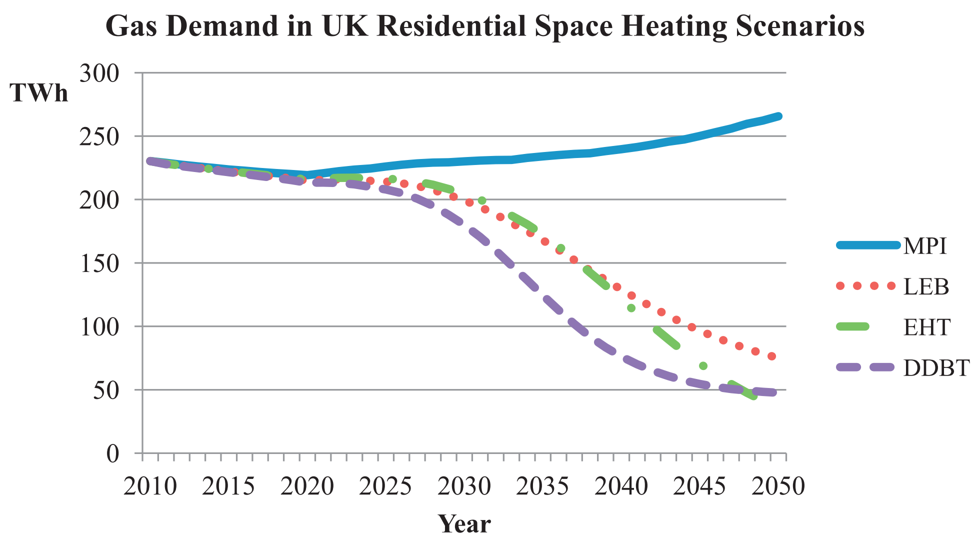

Fig. 3. Gas demand in UK residential space heating scenarios.

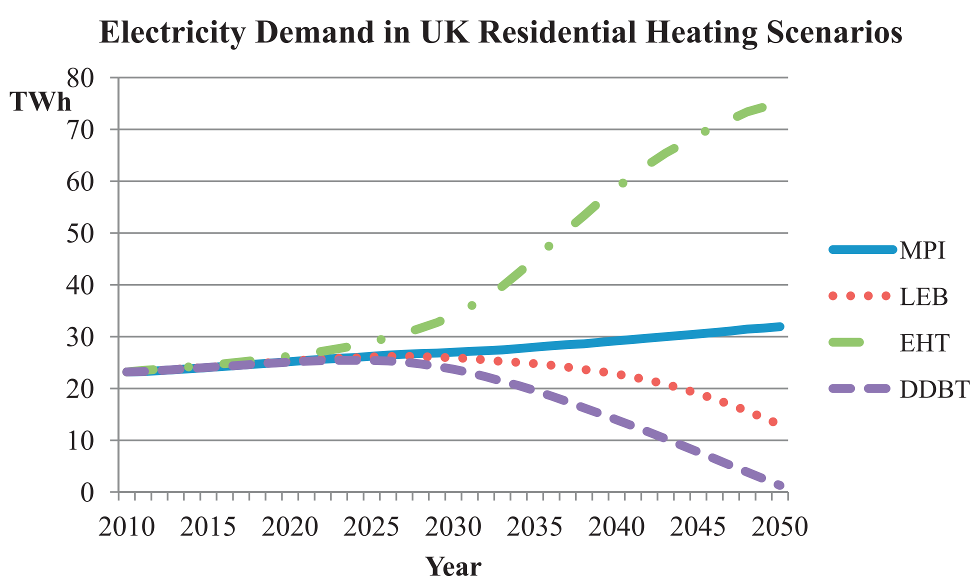

Fig. 4. Electricity demand in UK residential space heating scenarios.

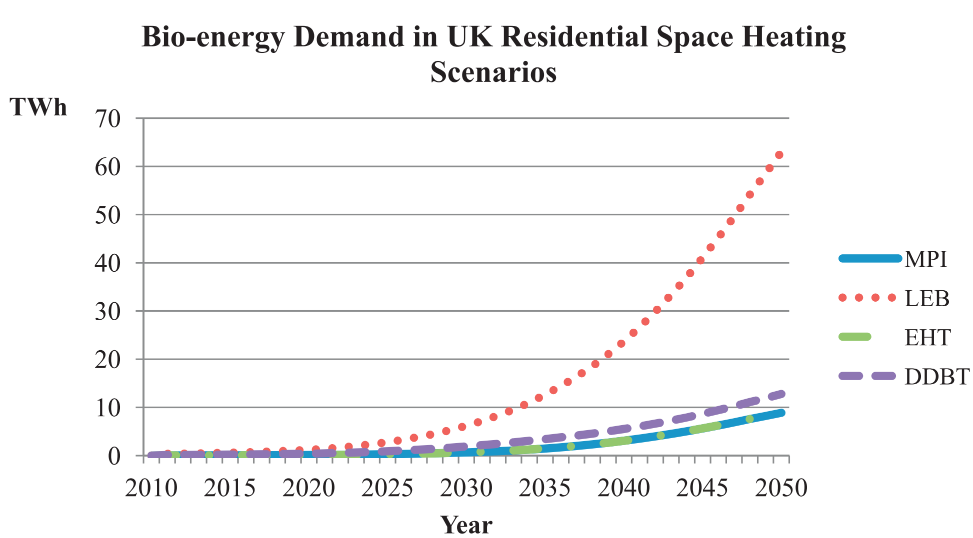

Fig. 5. Bio-energy demand in UK residential space heating scenarios.

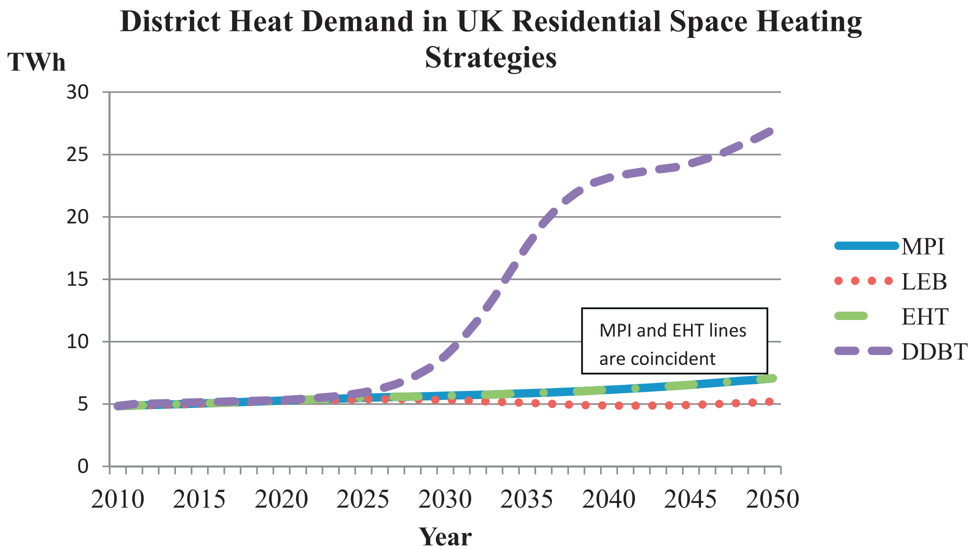

Fig. 6. District heating demand in UK residential space heating scenarios.

generation plant.

6. Discussion

The UK's ambitious greenhouse gas emissions reduction targets, especially for 2050, are widely interpreted to imply almost complete decarbonisation of residential heating services (CCC, 2013; HMG, 2011). However, our analysis shows that with minimal policy intervention, the UK will continue to use substantial quantities of natural gas for home heating, which is inconsistent with climate policy ambitions. The other scenarios investigated produce impacts on fossil fuel use, and their carbon emissions, which are broadly consistent with ambitious climate policy goals. Whilst rapid decarbonisation of electricity followed by wholesale conversion of heating to heat pumps is the most widely discussed strategy, it is not the only one. Other approaches place more emphasis on alternatives, notably biofuels and energy efficiency, indicating that there is some flexibility in delivering carbon mitigation policy, although a substantial emphasis on heat pumps seems likely.

The implications for different infrastructures are profound. With minimal policy intervention, the UK will remain dependent on a natural gas-fired heating infrastructure. Any move away from this creates a substantial reduction in gas demand, and consequential issues for owners of the gas infrastructure. With one notable exception (Dodds and McDowall, 2013), these are not well recognised in the research and policy literature and therefore warrant further attention. This 'destruction of demand' for gas might be mitigated by greater use of biogas through the existing infrastructure. The extent to which biogas can be sourced in a country with as high a population density as the UK is controversial, but the numbers set out in the high biomass scenario above (LEB) seem feasible without heavy reliance on imports. In principle, hydrogen (produced from biomass or any other low carbon energy source) might also be use either to enrich or substitute for natural gas. This would however require upgrading the gas infrastructure to accommodate higher level of hydrogen in the mix.

The scenario which places a very high dependence on electrification and heat pumps (EHT) poses challenges for electricity infrastructure – both distribution and generation. The additional space heating load of 75 TWh/year will be strongly peaked in winter, and heat pumps are less efficient at lower temperatures. Whilst heat storage and electricity system demand response, within buildings or elsewhere, can mitigate diurnal demand peaks,

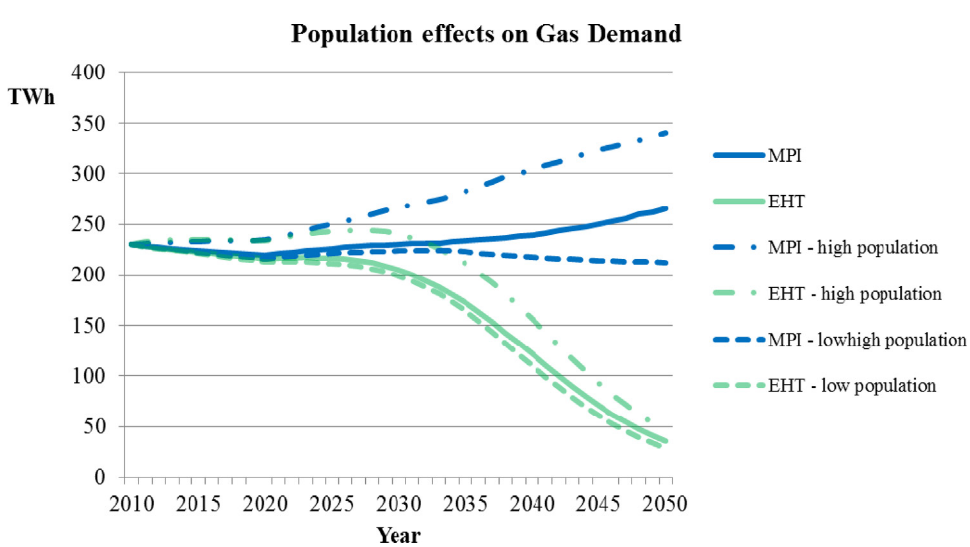

Fig. 7. The effect of population projection on UK residential gas demand.

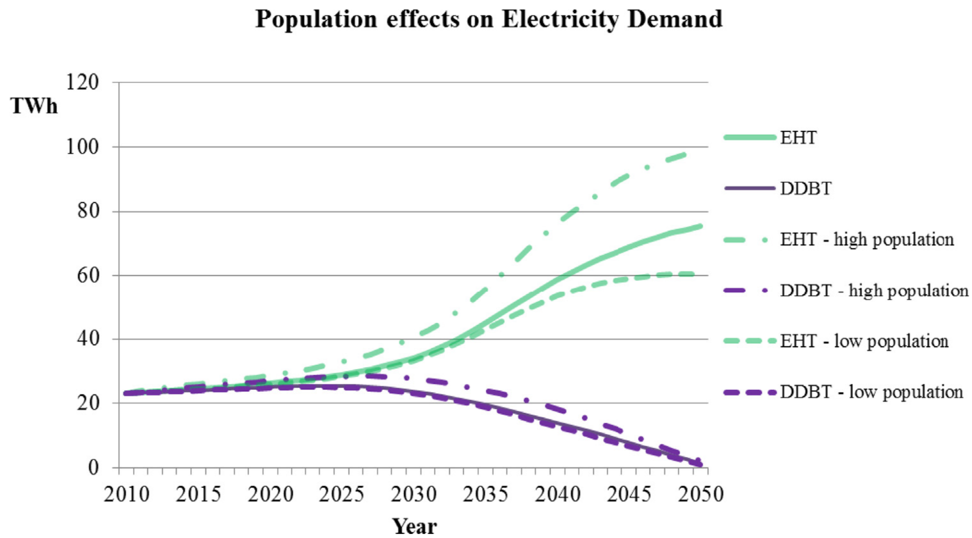

Fig. 8. The effect of population projection on UK residential electricity demand.

seasonal impacts cannot be mitigated without very large scale, and therefore very expensive, heat storage. Although the impact of 75 TWh/year spread equally over the year is approximately 9 GW, when the effects of seasonality and heat pump efficiency are taken into account, the impact on peak demand in cold weather in mid-winter will be over 40 GW on a Great Britain system where peak load is currently ~60 GW. Transport electrification will, of course, potentially exacerbate the effect (Tran et al., 2014).

The potential implications for electricity sector investment are very significant. Capital costs of power generation range from ~£500/kW for peaking plant to in excess of £3000/kW (declared net capacity) for low carbon technologies (PBP, 2011). We assume that, to meet carbon goals, the increase in average winter load (~20 GW) would need to be met by low carbon capacity, with the shorter term (diurnal and cold weather) peaks met by low capital cost technologies. This implies a generation programme to electrify residential heating demand would require investment of ~£70 billion. There will also be additional transmission costs, but these are likely to be an order of magnitude lower (Baruah et al., 2014b). This is additional to the cost of the heat pump and its installation, currently estimated to be £8000 per household, with the scope to fall to £5000 by 2030 (Element, 2012). Of course, other strategies are not cheap either, implying significant investments in the building stock, district heating and/or photovoltaics, but, in Great Britain, £70 billion is almost £3000 per household just for the additional generation capacity. These figures illustrate that attention is required to peak demand issues.

As a sensitivity, we have calculated the implications for additional power generation capacity investment if heat pumps were sized only to meet average winter conditions (~5 C), as opposed to cold weather conditions (~−5 C). We estimate the capacity requirement would be ~40% (~15 GW) lower if secondary heating systems are used only to meet the difference in heat demand caused by unseasonably cold temperatures.

Once secondary systems are installed, more radical options are possible, including replacing the whole of residential heating electricity demand at times of system peak demand. Fig. 9 presents the impacts of such an approach for the UK system in the EHT scenario, using back-up heating systems (for example a hybrid heat pump/gas boiler system) during times of system peak demand. The peak load on the GB electricity system is reduced by the full 40 GW of residential peak demand, reducing peak load by

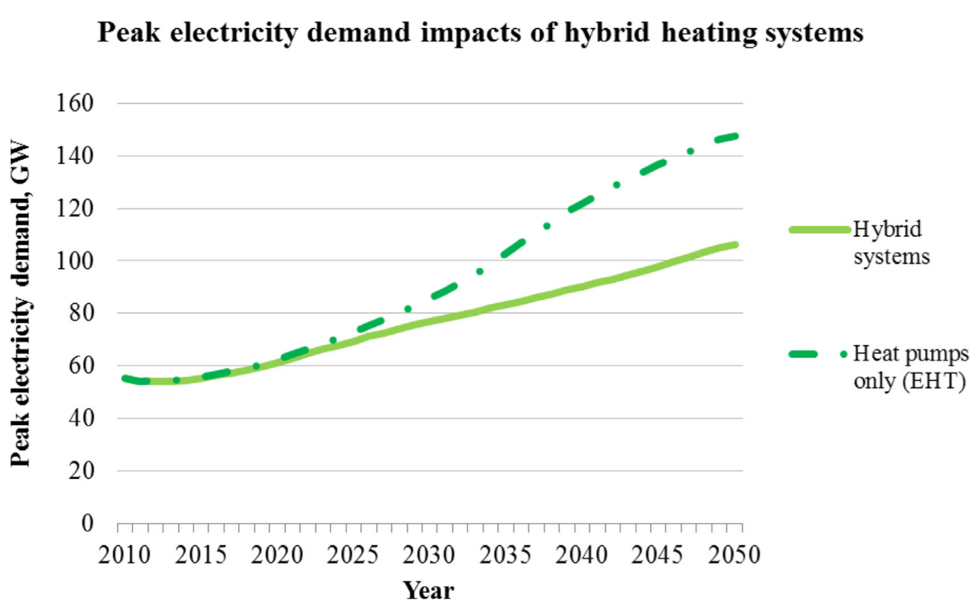

Fig. 9. Peak electricity demand in a high electrification scenario with and without back-up systems for meeting peak heat demand.

more than 30% (Baruah et al., 2014a).

If determination to deliver on carbon emissions goals is neglected, continued high dependence on gas looks the most probable outcome, if for no other reason than that the infrastructure exists. The corollary is that overcoming the gas 'lock-in' is essential to delivering climate mitigation goals. This has major implications not just for the energy sector, but for the myriad of small enterprises that deliver the end use technologies involved. The UK has approximately 100,000 gas fitters; the implications of the scenarios other than MPI is that these jobs need to be replaced by heat pump fitters (involving electrical and refrigeration skills), district heating providers, PV installers and a range of energy efficiency trades.

Uncertainties in socio-economic drivers, in particular population, have been neglected by most analysts and policymakers. They are certainly not as dramatic as the uncertainties arising from qualitatively different infrastructure systems. But they are significant and, in scenarios that are very heavily reliant on a single fuel, the uncertainty is concentrated in that fuel, so that high population projections exacerbate the investment implications of high electricity scenarios. On the other hand, strategies with high efficiency combined and on-site electricity generation reduce the range of demand uncertainty from demographic change. Other research (Cooper et al., 2013) has shown that there are economic synergies between heat pumps and micro-CHP, arising from the propensity of the latter to generate at times of highest heat pump demand. These benefits are not well represented in most energy system models, due to their limited temporal granularity. Micro-CHP systems have currently failed to enter the market in large numbers due to performance and reliability issues, but if these problems could be resolved, a mixed deployment of heat pumps and micro-CHP would have some significant advantages in peak load avoidance.

It seems very likely that the optimal strategy for delivering a low carbon residential heating system at minimum cost is a mixture of the three 'low gas' options set out above. The 'all electrification' strategy has a number of problems, not just electricity generation capacity needs. However, it remains difficult to see a very low carbon system without some element of this approach. Other options for system change also have associated risks. Greater reliance on efficiency requires delivery of high thermal performance in retrofitting that has yet to be widely achieved (Chiu et al., 2014). Greater use of biomass in CHP systems has led to a number of reliability problems and the technologies for both single dwellings (e.g. pellet boilers) and biomass gasification have not been widely deployed in the UK. The extent to which these risks will prove tractable cannot currently be known. This points to a short term strategy of 'opening options'. Whilst the costs associated with development, demonstration and early deployment of a number of options may be significant, they will be less than those associated with a whole-hearted commitment to a pathway that ultimately fails. The implication for public policy would seem to be that opening up all of these options is prudent at this stage.

6.1. Implications for the UK Government's Heat Strategy

In this sub-section we compare our analysis with that of the UK Government as set out in its Heat Strategy (DECC, 2013b) published by the Department of Energy and Climate Change (DECC). In the Heat Strategy, gas continues to play a major role into 2030s with diminishing role thereafter, but no role for gas boilers by 2050, by when heating demand is met by mass deployment of heat pumps, supplemented by urban heat networks (supplied largely from nuclear and CCS power stations). The primary modelling tool used to support this analysis, the Redpoint Energy System Optimisation Model (RESOM), suggests that hybrid systems comprising an air source heat pump with a supplementary gas boiler to meet peak demand (hybrid air source heat pump, HASHP) is likely to play a significant role, given carbon constraints, after 2020. Other modelling, with the ESME model (Heaton and Davies, 2010) suggests gas absorption heat pumps (GAHP) might also be able to play a bridging role. Nevertheless, 'no role for gas' by 2050 means HASHP and GAHP are seen as bridging technologies before electric heat pumps and district heat networks (supplied by low carbon technologies) take over. The RESOM core model runs indicate this bridging role, showing around 80% of residential and water heating delivered by heat pumps by 2050.

Our analysis is supportive of this analysis in so far as the heat pump uptake in our EHT scenario is broadly consistent with that in the Heat Strategy. Moreover, the inclusion of some different technologies, such as GAHP and HASHP, in the Government's Heat Strategy may help address some concerns about the over-reliance on ASHP, both in earlier UK Government analysis and our EHT scenario. However, our exploration of other social and technology issues, in the wider range of potential scenarios for UK residential heat policy that we consider, raises some important concerns about the Heat Strategy.

The Heat Strategy appears to under-represent the potential for building energy efficiency. Its analysis indicates building energy efficiency improvement by about 20% over 40 years (0.5% per year). This is substantially less than the recent rates of energy demand reduction in the sector, which are most probably due to building efficiency improvement, and small compared to the potential set out by DECC elsewhere (HMG, 2011). It seems to be inconsistent with DECC's own high ambition for improved building energy efficiency (DECC, 2010), as well as the legal requirements of the European Union's Energy Performance of Buildings Directive. There is no justification of the choice in the evidence annex to the Heat Strategy, nor any sensitivity analysis. It implies that the heating demands modelled are higher than is cost effective and therefore that the cost effectiveness calculations for new heating technologies are based on implausibly high demand, and therefore over-optimistic.

There is no explicit role for biofuel technologies in the Heat Strategy. The optimum use of biomass in carbon constrained economies is a complex topic, and many analyses find it is optimally used outside the building sector. However, there is no apparent exploration of the use of biofuels. Biomass boilers are listed in the technologies available to RESOM, but not deployed in the scenario reported. Biogas technologies are not listed. As biogas and hydrogen are the only plausible routes to retaining the dominant gas network, this omission risks pre-determining the importance of the other key network infrastructure-electricity. There is some use of biomass in supplying heat networks, but this is very limited by 2050.

The Heat Strategy modelling involves a remarkably rapid phasing out of gas boilers. These are assumed to be phased out by 2030, which implies no new installation after about 2018 if they are not to become stranded assets. For such a fundamental policy shift to occur for a key mass market product in less than 5 years seems highly improbable.

There are very optimistic assumptions about the deployment of HASHP in the Heat Strategy modelling. Energy output from HASHP rises to $\sim$30 TWh/year by 2015 (which clearly will not happen) and $\sim$100 TWh/year not long after 2020. This implies the installation of $\sim$1 million systems per year in the very near future, which is extremely optimistic for a technology that is currently deployed in very limited numbers.

The Heat Strategy itself, as opposed to the modelling supporting it, focuses on providing short and medium term incentives for heat networks in dense urban areas and low carbon, single home technologies for off-gas areas. These are initial niche investments that are reasonably robust against the different low carbon scenarios we have considered, and therefore our analysis tends to support the Heat Strategy itself, whilst conflicting with some of the modelling used in its evidence base.

There is no certainty that the projected long term outcomes of the Heat Strategy are those represented in the results of the models used by DECC. Such a heavy reliance on electrification has not been the outcome of analysis in other EU countries, in particular in Germany (Schlomann et al., 2014) and Denmark (DEA, 2014), where greater reliance is being placed on energy efficiency and alternative heat vectors respectively.

6.2. Implications for the UK 4th Carbon Budget

Given the importance of residential space heating for UK energy demand, and its current carbon intensity, there are obvious implications of this work for UK carbon mitigation. In this section we compare our key findings with the analysis of UK Committee for Climate Change (CCC) for the 4th Carbon Budget (CCC, 2013).

Reflecting its legal mandate, the CCC (CCC, 2013) outlines cost-effective pathways to meet the 2050 carbon target embodied in UK Climate Change Act. In this sense, it has very clearly different objectives and methods from our analysis. In the CCC analysis, energy prices and abatement costs are key factors in modelling technology uptakes into the future. In contrast, the focus of our analysis has been to draw out the possible uncertainties in heating energy demand from exogenous drivers and a diverse set of transition pathways. We make no attempt at strict cost minimisation, although, of course, the modelling assumptions reflect the fact that costs will be an important issue. So our assumptions about technology change are not solely dependent on prices, costs and demand elasticities. In essence, we assume that different, internally consistent, pathways of socio-technical change are possible under different economic, social and political conditions, rather than focusing on a single goal (climate mitigation) and minimising its costs as the CCC analysis is required to do.

The central population estimate in our scenarios aligns closely with the single projection used in CCC analysis. We consider that the absence of any alternative demographic assumptions in the CCC work is a significant weakness of their analysis. In particular, given the strong dependence on heating electrification in the CCC analysis (and that of DECC), neglecting the possibility of higher population growth implies under-estimating the risk of more problematic outcomes related to higher electricity use and peak demand. And the absence of alternative scenarios limits the capacity of their analysis to be robust against uncertainties in future demand, technology cost and end-user acceptability.

In our study, building envelope efficiency is modelled through transparent assumptions about the achievable rates of improvement of thermal performance of the building stock, ranging from modest changes to a 50% reduction in average heat loss by 2050. The latter is in line with the high ambition level for efficiency improvement in DECC's 2050 analysis, but less ambitious than set out in recent international assessments (Lucon et al., 2014; Urge-Vorsatz et al., 2012). The CCC uses more detailed 'bottom-up' modelling of individual measures, both energy efficiency (Element, 2013) and low carbon heating (Frontier, 2013). This provides a more robust basis for short to medium term assessment and costing, but neglects the potential for more radical low carbon upgrades in deep refurbishment. The CCC assessment of 50 $MtCO_2$ potential for energy efficiency is broadly consistent with the 50% improvement in energy efficiency assumed in our DDBT scenario. Both are far more ambitious than the potential of 20% in the DECC Heat Strategy, and this is a major source of analytical difference.

Conservation measures leading to reductions in internal temperature are slightly more ambitious in (CCC, 2013), with a 1 C temperature reduction by 2030, where as we assume a reduction of 0.5 C by 2035 and 1 C by 2050 in the DDBT strategy only. Recent energy use trends in UK housing imply that the trend towards higher internal temperatures has ended. This may be a temporary phenomenon associated with higher energy prices, but it implies that such modest downward changes are credible.

Our analysis of the potential for district heat networks is broadly similar to that of the CCC. The DDBT scenario is where we explore relatively high penetration of district heat networks, reaching 2% by 2030 and 20% by 2050. The 4th Carbon Budget report raises the CCC goal to 6% of heat demand by 2030, in the context of new evidence suggesting a potential of 40% by 2050. However, closer examination of the 40% number indicates that the majority (28%) is contingent on heat recovery from large power plants, which we judge to be uncertain. Our 20% estimate is consistent with heat mapping (Poyry, 2009), which estimated that 20% of UK heat demand is at densities exceeding 3 MW/km^2.

Despite the increased focus on district heating in the 4^{th} Carbon Budget report, the predominant technical change remains towards heat pumps, principally ASHP. The 4th Carbon Budget report projects 30.6 million household heat pump installations are required by 2050 to meet the carbon target, supplying 232 TWh to 80% of all properties. The number of installations by 2030 has been revised down from a previous estimate of 7 million, based on supporting analysis, due to relatively slow progress to date (Element, 2013). The 4th Carbon Budget report projects a heat pump market penetration of 4 million by 2030, i.e. ~13% of the total housing stock. The pathway is broadly consistent with EHT scenario set out in our analysis, i.e. it is a pathway that still moves decisively towards electrification of heating, with all the benefits and risks set out in our analysis of the EHT scenario above. As shown in Fig. 10, it requires approximately double the substitution of gas boilers by heat pumps compared to a more diverse strategy such as modelled in our DDBT scenario.

In contrast to the DECC Heat Strategy, the 4th Carbon Budget Report does not include quantified projections for hybrid heat pumps or gas heat pumps, due to the commercial uncertainties in their availability and performance. There is qualitative attention to GAHP, noting their benefits in peak electricity reduction. The supporting analysis to (CCC, 2013) has conducted a sensitivity analysis of HASHP deployment. This notes that HASHP will have some important advantages: better compatibility with higher heat loss buildings and existing heating systems; a lower cost of adapting the heating systems; reduced heat pump capacity making the installation costs comparable to ASHP; and improved performance (a Seasonal Performance Factor 0.3 higher than an ASHP). Most importantly HASHPs can be installed as an addition to an existing boiler. On the other hand, space and environmental (noise and visual) constraints may be broadly similar and the operating costs will be comparable. Importantly, the carbon benefits of HASHP are lower than ASHP and GSHP. However, the CCC analysis provides no quantified evidence on HASHPs' ability to reduce peak load. Neither is the attractiveness to users of installing quite complex heating systems in low energy homes explicitly considered.

Overall, the supporting analysis for the 4th Carbon Budget report finds that HASHP can reduce the need for conventional heat pumps in 2030. However, it agrees with the DECC Heat Strategy analysis that the imperative of meeting the 2050 carbon target leaves no role for gas-based systems, and therefore requires phasing out of HASHP by 2050. The implications of our analysis for the CCC projection are therefore similar to that for the DECC heat strategy: that reliance on a single strategy with high levels of electrification lacks robustness against technical, commercial and policy risks to mass deployment of heat pumps.

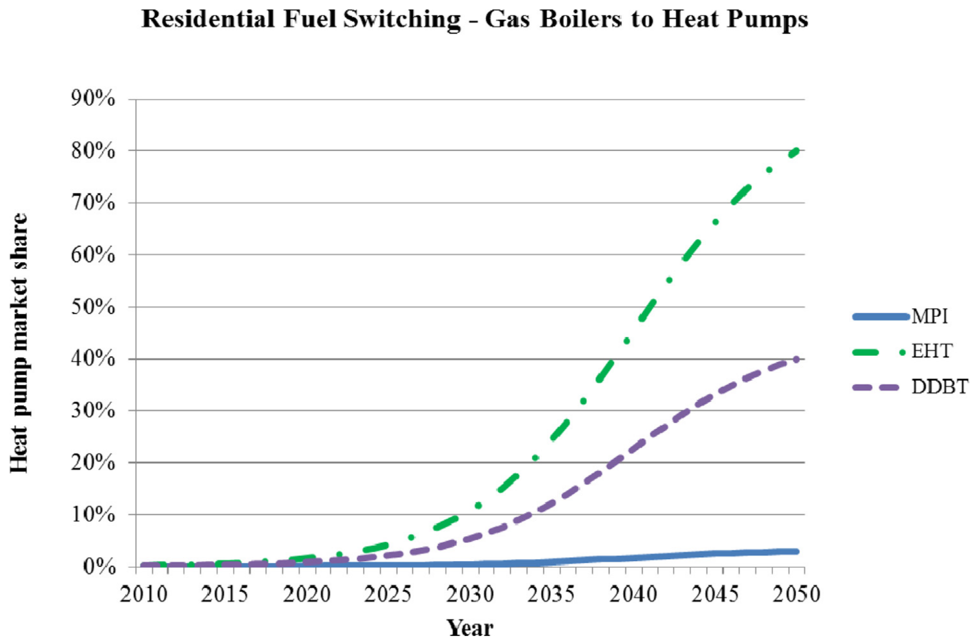

Fig. 10. Heat pump substitution for gas boilers.

7. Conclusions

Direct use of fossil fuels is the main source of space heating in the UK and this drives a major part of national greenhouse gas emissions. Climate stabilisation therefore implies a systemic change in approaches to space heating, involving some combination of radical efficiency improvement and low carbon vectors. The challenge in this area for the UK is made particularly difficult because of the combination of the legal commitment to an 80% reduction in emissions by 2050, an inefficient building stock and a very high penetration of natural gas as a heating fuel.

We present new quantified scenarios for residential energy use in the UK to 2050. These address both factors that are exogenous to the energy system, such as population, but also some systemically different approaches to delivering residential heat.

With minimal policy intervention the UK will remain locked into a gas based heating system, but there is a range of scenarios in which this is avoided. Heat pumps powered by low carbon electricity are an option, but complete reliance on this as a solution raises a number of problems. Very high levels of electrification imply the disuse of much of the gas infrastructure and major changes in heating installer products, supply chains and practices. The performance and acceptability of heat pumps in UK homes remains unproven. Meeting peak heating demand with heat pumps alone would need approximately 40 GW of additional electricity generation capacity, much of it low carbon, at an investment cost of approximately £70 billion. These pressures might be exacerbated by high population growth. However, they might be reduced using some hybrid heating technologies, notably hybrid boiler/heat pump systems as bridging technologies, although these are currently unproven and may be difficult to deploy at scale by 2030.

Much greater use of energy efficiency and biomass can also play a significant role in decarbonisation and diversify the risks associated with a high electrification strategy. Substantially higher use of biofuels raises concerns about sustainable sourcing, but seems feasible within projected available resources. There is also a potential role for heat networks in dense urban areas, but this still requires low carbon sources, if heat is to be decarbonised. Improved efficiency is helpful in reducing overall demand, and therefore reduces costs and pressures on supply side solutions.

Meeting low carbon heating goals is better conceptualised as reducing reliance on gas (and other fossil fuels) rather than necessarily mass electrification. Any low carbon heating system will require the deployment of unfamiliar technologies at scales requiring major investment and changes in supply chain practices and consumer acceptance.

We conclude that the future of UK residential space heating is very uncertain. Either gas or electricity could be the major fuel supplier; and biofuels and district heating might or might not make significant contributions. The nature of the required infrastructure is very different in each case. A continuation of the existing pattern of demand with a heating sector dominated by natural gas is possible, but conflicts with current UK policy goals for decarbonisation. UK policy makers currently preferred alternative is a system heavily reliant on heat pumps supplied with low carbon electricity. We conclude that some shift in this direction is very likely to be required to meet current UK policy objectives, but that a very heavy reliance on this approach poses a number of risks. A more diversified strategy, with greater emphasis on energy efficiency and biofuels has lower risks, and therefore is more prudent.

Our analysis focusses on the UK, but has implications for any country with high demand for fossil fuels to provide space heating in buildings and ambitious decarbonisation goals. Some move towards electrification of heating seems very likely, but the risks, in particular, to peak winter electricity demand need to be more carefully considered than in most analyses to date.

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